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Impact of no-till and mulching on soil carbon sequestration under rice (*Oryza sativa* L.)-rapeseed (*Brassica campestris* L. var. rapeseed) cropping system in hilly agro-ecosystem of the Eastern Himalayas, India

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ABSTRACT

Decline in soil organic carbon (SOC) and low biomass production in sloping uplands are of growing concern for sustainable agriculture worldwide. This concern is in general in the Eastern Himalayan regions (EHR) of India in particular. A field experiment was conducted with the objectives to generate additional biomass and sequester more C in coarse-textured sloping lands. This experiment is done for four consecutive years in the EHR, India. The rice (*Oryza sativa* L.)–rapeseed (*Brassica campestris* L. var. rapeseed) cropping system was practiced during the first two years (2012-13 to 2013-14) and rice–rapeseed–cowpea (*Vigna unguiculata* L.) system during the two following years (2014-15 to 2015-16) of the study under different tillage and mulch systems. The tillage system included: 1) CT-RI: conventional tillage (CT) with 100% residue incorporation (RI) and 2) NT-RR: no-till (NT) with 100% residue retention (RR). The mulches included 1) rice straw mulch (SM), 2) *Gliricidia* sp. mulch (GM), 3) brown manuring mulch (BM)–cowpea grown as intercrop with rice up to 40 days after sowing (DAS), killed with 2,4-D and 4) no mulch (NM). The cowpea, as a cover crop was introduced during 2014 and 2015 as pre-rainy season crop before the sowing of rice to generate additional biomass in the system. The four year total above ground biomass yield of rice and rapeseed didn't vary significantly between CT-RI (31.93 and 17.40 Mg ha^{-1}) and NT-RR (31.86 and 17.46 Mg ha^{-1}), respectively. However, the total above ground biomass yield of cowpea was more under NT-RR (10.75 Mg ha^{-1}) when compared to that under CT-RI (9.79 Mg ha^{-1}). The amount of total biomass (above + below ground) and C added into the soil was more under NT-RR than that under the CT-RI. After 4 cropping cycles, the NT-RR had higher SOC concentration, pool (29.9 vs. 29.1 Mg ha^{-1}), sequestration rate (450 vs. 265 kg ha^{-1} yr^{-1}) and C retention efficiency (7.7 vs. 4.6%) than those under the CT-RI at 0–30 cm depth. The mulched plots produced more crop biomass (both above and below ground), recycled more C in soils with a trend of relatively more SOC pool (29.7–29.8 vs. 29.0 Mg ha^{-1}), sequestration rate (391–428 vs. 221 kg ha^{-1} yr^{-1}) and C retention efficiency (6.64–6.94% vs. 4.66%) than those of NM treatment. These results were seen despite difference among the mulch treatments (SM, GM and BM) which were statistically non-significant after 4 cropping cycles. Inclusion of cowpea as cover crop during pre-rainy season in the system doubled the rate of C sequestration (478 kg C ha^{-1} yr^{-1}). Therefore, the data supports the recommendation of cultivation of the rice–rapeseed system under NT-RR along with cowpea intercropping up to 40 DAS (BM) in rice. Besides this, the inclusion of pre-rainy season cowpea before rice could generate additional biomass and enhance SOC sequestration on upland and sloping hills in the EHR of India and in similar conditions elsewhere.

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1. Introduction

The soil carbon (C) pool is an important component of the global C cycle. Estimated to 1-m depth, world soils contain 1505 Pg (Pg = petagram = 10^{15} g = 1 billion metric tone) of soil organic carbon (SOC) and 750 to 950 Pg of soil inorganic carbon (SIC) (Lal, 2018). World soils have lost 90 to 135 Pg of C upon conversion from natural to human managed ecosystems due to excessive tillage, residue removal/burning, and soil degradation caused by erosion and other processes (Paustian et al., 2016; Lal, 2018). Thus, the soil C pool and its dynamics strongly impact the global C cycle and the atmospheric chemistry by moderating the emission of greenhouse gases (GHGs) (Ladha et al., 2016). Further, there is an urgent need for developing a strategy of "net negative emissions" for minimizing the risks of climate change (Holden et al., 2018). Most scenarios of limiting the global temperature change to below 1.5 °C or 2 °C involve C sequestration as potential mitigation strategy (Seneviratne et al., 2018). In addition, the SOC is also a primary determinant of soil fertility, crop productivity and environmental sustainability (Ladha et al., 2016). Soil quality and productivity are directly related to the SOC pool and its dynamics (Kumar et al., 2018). It increases aggregate stability, water holding capacity (WHC) and supply of essential nutrients to the crops (Yadav et al., 2017a). Therefore, it is an important indicator of sustaining productivity and agricultural ecosystems (Choudhury et al., 2016). The SOC pool of Indian soils ranges from 24 to 63 Pg to 1.5 m depth. However, most of the degraded and depleted soils in India contain SOC concentration below the threshold level of 1.1 to 1.5%, and hardly contain 10 to 15 Mg C ha^{-1} to 40 cm depth (Lal, 2015a). The SOC pool is persistently diminishing in Indian soils because of improper agriculture management practices. The SOC pool in the Eastern Himalayan regions (EHR) of India is emphatically influenced by the climate change, extractive farming practices and the anticipated changes in temperature and the precipitation. All these factors may further reduce the SOC pool (Das et al., 2017). Severe reduction of SOC can cause a range of problems including water pollution, air pollution, sedimentation, soil degradation, and GHGs emission in India and elsewhere in South Asia (Ladha et al., 2016). Therefore, there is a need to identify some important "bright spots" for ecosystem C sequestration through identification and adoption of the best management practices (BMPs).

The EHR of India, covering a total geographical area of 26.27 million hectare (Mha), includes Indian state of Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Tripura, Sikkim and hilly tracts of Assam. The EHR region is characterized by sloping hills, mountains and plateaus with near tropical to alpine climatic conditions (Das et al., 2016). Most soils of the region contain 0.5 to 3.56% soil C in surface 0 to 30 cm depth and contribute 19, 1 and 13% of SOC, SIC and total C pool of the nation's soils, respectively (Bhattacharyya et al., 2008). Indian states of Assam and Tripura have low SOC content due to prevailing warmer climate than that in the rest of the region (Choudhury et al., 2013). The wide variation in SOC content in the region shows a great potential of C sequestration and soil of subtropical ecosystems of Tripura and other parts of the EHR which may be a "bright spot" to sequestrate C for climate change mitigation in India. A decline in the SOC pool in the region is a genuine concern mainly because of the intensive tillage without proper input of biomass-C, deforestation and shifting cultivation (slash and burn agriculture) on sloping and hilly areas. The decline of SOC concentration by more than 30% upon conversion of forest land to shifting cultivation has been reported from the region (Choudhury et al., 2016). Decline in the SOC is further exacerbated by intense soil erosion from plowed and bare fields (with no soil cover). Similarly, cultivation of rice (*Oryza sativa* L.) using conventional tillage (CT) with inadequate residues input reduces SOC (19 to 34.6%) pool (Choudhury et al., 2016). This reduction happens through oxidation, burning of crop residues causing CO_2 emissions, and loss of essential plant nutrients (Das et al., 2017). Rice, the staple food crop of the region, is cultivated on ~3.5 Mha, and accounts for almost 8% area and 6.5% of the India's rice production (Choudhary et al., 2017). Therefore, rice-based cropping is the predominant farming system which is practiced across three landforms: upland, wetland, and terraced lands in the EHR (Yadav et al., 2017b). Rapeseed (*Brassica campestris* L. var. rapeseed) is a popular oilseeds crop of the region and grown on ~ 0.32 Mha after harvest of the rice/maize (*Zea mays* L.) on residual soil moisture (Das et al., 2017). Furthermore, the region has ~ 1.5 Mha rice-fallow lands which offer a large potential for horizontal expansion of rapeseed cultivation. Accordingly, rice–rapeseed (mustard) cropping system occupies an important place in the agricultural economy of the EHR (Ghosh et al., 2010). Both crops contribute significantly towards the livelihood of millions of small landholder farmers engaged in the region (Ghosh et al., 2010). But the productivity of both crops are low as they are grown on marginal lands including sloping uplands, with low SOC content and poor inherent fertility (Yadav et al., 2015; Das et al., 2017). Thus, total plant biomass (both above and below ground) production of cultivated crops under such condition is low, which further depletes the SOC and increases CO_2 emissions (Choudhury et al., 2016). The low crop productivity and increasing population pressure force farmers to bring more land area under cultivation through deforestation. Through enactment of the Recognition of Forest Rights Act 2006 by Government of India, 8 Mha of forest land was brought under cultivation in the EHR of India. Clearly, this situation may affect not only SOC, but also the water balance in the region (Nosetto et al., 2012), with global consequences. Therefore, the region requires a wide adoption of BMPs-based cropping systems, which can restore the SOC through sufficient plant biomass production. This process will enhance advancement of food security and mitigation of climate change (Lal, 2015a). The SOC sequestration and protection of native carbon are important for improving the soil quality and mitigating GHG emissions through adoption of conservation-effective agricultural practices (Lal, 2015b).

The conservation agriculture (CA), involves minimum soil disturbance, permanent soil cover, and diverse crop rotations, restores SOC, helps achieve higher productivity and minimizes adverse environmental impacts (Das et al., 2013; Lal, 2015a). However, the impact of CA has not been assessed for rehabilitation of degraded lands and sustainability of productivity in the most fragile EHR ecosystem. Therefore, areas with sloping uplands and coarse-textured soil can be sustainably managed by no-till (NT) with mulch or residue retention (an important pillar of CA). Adoption of NT may increase crop yield and biomass production, and enhance the input of biomass-C into the soil (Das et al., 2017). Retention of crop residues on the soil surface may improve soil quality and resource use efficiency (Gathala et al., 2013). Further, crop residue mulch has a range of advantageous effects e.g., regulating soil temperature, enhancing nutrient supplying capacity of soils, improving soil health, etc. (Sharma et al., 2010). However, crop residues especially rice straw has other competing uses like feed for cattle during the lean periods (Ladha et al., 2016). Therefore, biomass from other sources (i.e., leaves and twigs of leguminous perennial trees) may offer a good option as mulching materials (Mulvaney et al., 2017). The only limitation is that it involves additional costs towards collection and transportation of biomass (Yadav et al., 2018a). Another option is the adoption of legume co-culture (brown manuring-BM) practice for a specific part of the life cycle of a crop to generate nutrient rich *in-situ* biomass, which may be more an important option for procuring mulch from outside the fields. However, the rate of C input addition into soil under residue retention/mulching is not objectively studied for soils of the hilly agro-ecosystems of the EHR.

Review of available literature indicates that conversion to a NT system can sequester SOC at a wide range of 0.1 to 1.35 Mg ha^{-1} yr^{-1} under diverse climate and management practices (West and Post, 2002; Lal, 2004; Paudel et al., 2014; Du et al., 2017; Ghimire et al., 2017; Samal et al., 2017; Kumar et al., 2018; Büchi et al., 2018; Fujisaki et al., 2018; Nicoloso et al., 2018). However, there are reports that the benefits of NT- based CA are often an artifact of pedo-climatic conditions

and are smaller than those reported earlier (Poeplau and Don, 2015). Most of the claims of CA sequester SOC in soils and helps in mitigating climate change (Powlson et al., 2016) are presently under revalidation. Contradictions are mainly on the quantity of SOC restoration and distribution. Published studies highlighted that there are smaller changes in SOC pools under NT than that under CT (Corbeels et al., 2016). These are supported by contrasting results of various studies reported from different regions and cropping situations (Jat et al., 2014; Vanlauwe et al., 2014; Pittelkow et al., 2015; Powlson et al., 2015; Ratnayake et al., 2017). Despite this, the impacts of NT on changes in SOC pools in developing counties, having smaller farm holdings are not well known. This is further substantiated by two global-meta analytical studies; 1st one included 81 sites out of which 87% were from North America (Govaerts et al., 2009) and 2nd one included 49 data sets that has only 13 sites from tropical countries (Mangalassery et al., 2015). Powlson et al. (2016) reviewed the studies on NT conducted under tropical agro-ecosystem which included 29 data sets and found that SOC increased by 160-490 kg ha^{-1} yr^{-1} in the Indo-Gangetic Plains (IGP) and 280-960 kg ha^{-1} yr^{-1} in Sub-Saharan Africa compared with that under CT. Further, inclusion of cover crops in NT-based cropping system has been reported to accumulate SOC in the range of 0.1 to 1.0 Mg ha^{-1} yr^{-1} as compared to those without cover crops (Blanco-Canqui et al., 2013; Poeplau and Don, 2015). Till date, cover crops have been in the limelight mainly for their capacity to improve soil quality and thereby to foster crop production (Lal, 2004; Rosenzweig et al., 2018). The potential of cover crops to increase SOC pools and thus, to mitigate climate change has been highlighted in only a few studies (Lal, 2004; Rosenzweig et al., 2018).

Most of the NT-based technologies evaluated in India, especially those in the IGP and Southern India, were focused on agronomic productivity, water use, energy use and weed management (Kumar et al., 2017; Trivedi et al., 2018). Relatively few studies based on NT conducted in the EHR of India were focused on assessing the impact on productivity, profitability, water and weed management, and energy use (Das et al., 2017; Yadav et al., 2018a,b). However, monitoring of the impact of NT-induced changes in SOC pools under different management practices was important to identify site-specific BMPs. These site-specific BMPs increase SOC pools and restore the C to the original state. However, impact of NT on C-sequestration potential and changes in SOC pools in the EHR have not been widely investigated. Even though the ecosystem benefits and services associated with NT/CA are globally recognized, there is a lack of consistency in improving the SOC pool in the entire soil solum. Thus, it is important to note that the C sequestration potential of NT be assessed in fragile soils and ecosystems of the EHR. Changes in SOC pools under NT, with retention of crop residues and incorporation of a cover crop (cowpeas) in a direct seeded rice-mustard cropping system have not been evaluated in the EHR of India. Addressing these knowledge gaps necessitate a systematic evaluation of the impact of NT with retention of biomass of the whole system. This can be done with and without cover crop in the rotation cycle, on SOC sequestration in the EHR. This assessment is specifically needed with regard to the SOC sequestration potential of rice-mustard system with and without cowpea in the EHR.

Therefore, the present study was conducted to assess the effect of NT with residue retention as mulch on SOC sequestration potential of the rice-based cropping system in the EHR of India. In this agro-ecosystem, the soil remains fallow even during the pre-monsoon rains received during April to May. Thus, this study was designed to utilize these pre-monsoon rains to grow the cover crop (cowpea) for increasing biomass production and its inputs into the system. Specifically, the study analyzed the impact on SOC sequestration of the novel approach of including a cowpea cover crop during the summer season before seeding the rainy season rice into the rice-rapeseed cropping sequence. The specific objectives of the experiment were to: (i) assess the impact of the CA/NT with residue retention on biomass production, soil C sequestration and retention, and (ii) evaluate the relationship between C added and retained after four years of residue management and mulching in a sandy loam soil of the EHR of India. The experiment was designed to test the hypothesis that NT with residue retention along with mulch would produce more biomass and retain higher SOC compared to those under CT with residue incorporation. Furthermore, inclusion of legume (cowpea) as a cover crop would generate additional biomass in the system and increase the SOC pool.

2. Materials and methods

2.1. Experimental site

Field experiments, involving the rice–rapeseed system during 2012-13 to 2013-14 and rice–rapeseed–cowpea system during 2014-15 to 2015-16 under different tillage and mulch systems, were conducted at the Indian Council of Agricultural Research (ICAR) Complex for North Eastern Hill Region, Tripura Centre, Lembucherra, Tripura, India. The site is located at 23° 54′ 24.02″ N and 91°18′ 58.35″ E latitude at an altitude of 52 m above sea level. The region is characterized by sloping upland, and hot and humid summer, and a mild and dry climate during winter. The long term annual average rainfall of the region is 2200 mm. The details of rainfall, along with the maximum and the minimum temperatures, are presented in Fig. 1. Soil of the experimental site was sandy loam in texture, fine, Kaolinitic, Typic Kandiudults, and classified as Acrisols (Datta and Singh, 2007). The baseline soil samples were collected from 10 randomly selected spots from 0 to 30 cm depth at 10 cm interval and were composited for analysis prior to establishing the experiment. A detailed analysis of initial soil from the experimental

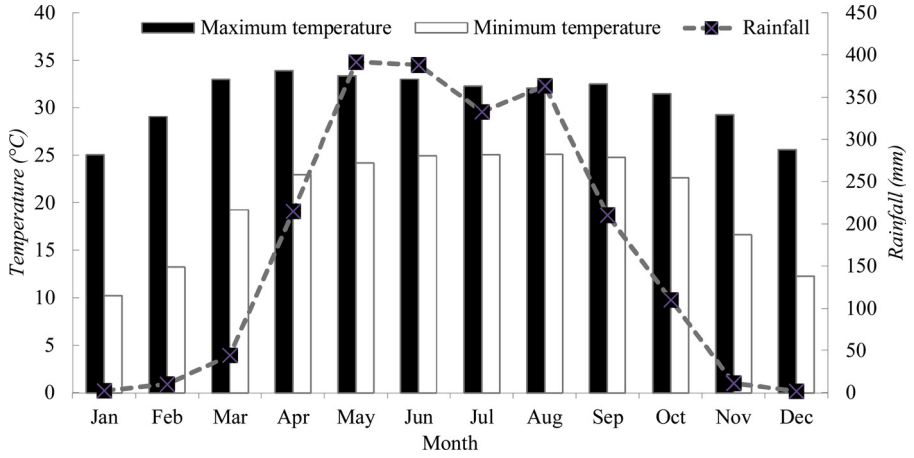

Fig. 1. Mean monthly maximum temperature, minimum temperature and rainfall of experimental site during 2012–2016.

Table 1
Physical and chemical properties of soils of experimental site.

Soil properties	Soil depth			Method
	0-10 cm	10-20 cm	20-30 cm	
Sand (%)	48.2	49.0	51.1	International pipette method (Piper, 1950)
Silt (%)	5.0	4.8	4.6	
Clay (%)	46.8	46.2	44.3	
Bulk density (Mg m^{-3})	1.42	1.44	1.47	Core method (Blake and Hartge, 1986)
Soil organic carbon (g kg^{-1})	6.3	6.1	5.9	Dry combustion method (Nelson and Sommers, 2005)
Available nitrogen (mg kg^{-1})	130.3	125.8	115.6	Prasad et al. (2006)
Available phosphorus (mg kg^{-1})	24.6	21.3	18.6	Prasad et al. (2006)
Available potassium (mg kg^{-1})	135.7	130.2	128.8	Prasad et al. (2006)
pH	5.2	5.3	5.3	Prasad et al. (2006)

site is presented in Table 1.

2.2. Experimental design and treatments

The experiment was laid out in a split-plot design, with 2 tillage and residue management practices as the main plot and 4 mulch types as subplot treatments with three replications. Thus, in total, there were 8 treatment combinations and 24 plots. Two tillage treatments comprised: (1) CT-RI: conventional tillage (CT) with 100% residue incorporation (RI) and, (2) NT-RR: no-till (NT) with 100% residue retention (RR). Details of cultural operations adopted under different tillage treatments are presented in Table 2. Mulching treatments included: (1) rice straw mulch (SM), (2) *Gliricidia* sp. mulch (GM), (3) brown manuring mulch (BM), and (4) no mulch (NM). Tillage treatments were imposed on all crops and mulch treatments only on rice at the time of sowing. The SM consisted of rice straw applied at the rate of 2.5 Mg ha^{-1} on dry weight basis. In case of GM, the leaves and twigs of *Gliricidia* sp. (a leguminous shrub species which has the potential as green leaf manure and hedge row plant for soil and water conservation in sloping lands) were cut and carried from *Cocotila* farm of the Institute and applied at the rate of 2.5 Mg ha^{-1} on dry weight basis. Under BM, one row of cowpea was sown as intercrop in between every two rows of rice at 10 kg seed ha^{-1}. Intercropped cowpea was killed by spraying 2, 4-D 0.5 kg active ingredient (ai) ha^{-1} at 40 days after sowing (DAS) and retained on the surface as *in-situ* mulch. A constant amount of mulch at 2 Mg ha^{-1} was maintained in all plots under BM by adding cowpea biomass from the nearby general plots, whenever required. The rice-rapeseed cropping system was managed under the above treatment during the first two years (2012-13 and 2013-14). However, in the third cropping cycle (2014-15), cowpea was included as a cover crop and seeded during summer (in the pre-rainy season) before rainy season rice under the rice-rapeseed cropping system. The objective of growing cowpea was to utilize the pre-monsoon rainfall and generate additional quality biomass in the system.

2.3. Crop management

The drought tolerant and short cycle (105–110 days) rice variety "Sahbhagi" was direct-seeded manually at 50 kg seed ha^{-1} at 25 cm row to row spacing. Rice was seeded during the 2nd fortnight of June and harvested during the 2nd fortnight of October. After the harvest of rice, short duration (85–95 days) rapeseed variety "TRCT-1-5-1-1" was seeded manually at 5 kg seed ha^{-1} at 30 cm row spacing. It was seeded during the 1st fortnight of November and harvested during the last week of February to the 1st week of March every year. The fast growing local cowpea variety "*Yellow dal*" was used as cover crop prior to

Table 2
Details of different cultural operation/activities performed under tillage treatments.

S.N.	Cultural operations/ activities	Tillage treatments	
		CT-RI	NT-RR
1.	Crop	All crops (rice, rapeseed and cowpea)	All crops (rice, rapeseed and cowpea)
2.	Disc harrowing	One-time uto10 cm depth to incorporate the crop residues and other biomass e.g., weed and mulch biomass, 7 days before sowing of each crop	–
3.	Tillage with power tiller	Three times tilling with power tiller before sowing of each crop to prepare good seedbed for better seed soil contact (upto 20 cm depth).	–
4.	Leveling	One-time, after final power tilling, field was leveled with a bamboo made power tiller attachment (Locally known as *Chakam*)	–
5.	Crop residue management	100% residue of previous crop was incorporated 7 days before sowing of succeeding crop	100% residue of preceding crop was retained on the soil surface during cultivation of succeeding crop
6.	Glyphosate	–	It is a general vegetation killer, was applied 5 ml l^{-1}, 7 days before sowing of each crop
7.	Sowing	Line sowing was done in each crop. Seed was placed manually in a furrow opened with local made wooden plow	Line sowing was done in all the crops. Seeds were manually placed in furrow opened with a NT furrow opener made by engineering division of ICAR-NEH, Umiam, Meghalaya.
8.	Principle of conservation agriculture		
a.	Minimum soil disturbance	–	Followed
b.	Permanent soil cover	–	Followed
c.	Diverse crop rotation	Followed- first two years (2012-14): rice-rapeseed system and last two years (2014-16): cowpea-rice-rapeseed system	Followed- first two years (2012-14): rice-rapeseed system and last two years (2014-16): cowpea-rice-rapeseed system

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention.

establishing the rainy season rice. The cowpea was sown at 20 kg seed ha^{-1} at row spacing of 25 cm during the 1st week of April. The cowpea biomass was incorporated before the sowing of rice in CT and suppressed by herbicides (Glyphosate 5 ml l^{-1}) and retained on the surface as mulch in case of NT. Cowpea and rice crops were grown during the pre-rainy (April to June) and rainy season (July to October), respectively without any irrigation. However, two supplemental life saving irrigations (20 mm water per irrigation) were given to rapeseed, the 1st during the vegetative (30 DAS) and the 2nd during the flowering stage (60 DAS).

A fertilizer dose of 60:18:33 kg N:P:K per hectare was applied in rice. Total amount of P and K, and half of N were applied at the time of sowing of rice. The remainder (50%) of N was applied through two equal split applications at 30 and 75 DAS, respectively. The same amount of fertilizer was also applied to the rapeseed in a similar manner but the remaining N was applied in two equal splits at 30 and 60 DAS. The cowpea was grown on residual fertility without any additional fertilizer. Glyphosate, a general vegetation killer herbicide, was applied as 5 ml l^{-1} about a week before sowing of all crops under NT plots. The pre-emergence herbicide, pendimethalin was applied at the rate of 1 kg ha^{-1} in rice and rapeseed within 2–3 DAS under both CT and NT systems. One hand weeding was given at the time of thinning at 20 DAS in rice and rapeseed to maintain the required plant population and manage the weeds. Neither weeding nor thinning was done in cowpea. The observation on the growth parameters, above and below ground biomass, and the yields were recorded in all crops at harvest.

2.4. Harvesting and biomass measurement

Both rice and rapeseed were harvested manually using traditional sickles. Grains were harvested along with ~50% of vegetative parts of crops. Following the manual threshing, crop residues were returned back to their respective plots. Grain yield of rice was reported at 14% and that of rapeseed at 10% seed moisture content. Grains were not harvested from cowpeas, and whole of its biomass was left in their respective plots. The straw/stover weight of rice, rapeseed and cowpea were measured from one square meter area in each plot after oven drying at 60 ± 1 °C temperature. Root samples were obtained at the harvest of rice and rapeseed, and before the incorporation of the cowpea. Root samples were obtained from 30 cm depth in each season using a core sampler (5.8 cm height and 5.4 cm diameter). The soil cores with roots were soaked in water for at least 12 h following the procedure described by Bohm (1979). The soil–root suspension was stirred in water and then passed through a 0.5 mm sieve. The roots were cleaned off the soil, and the dead organic debris and the fresh roots were oven-dried at 70 ± 1 °C till constant weight. The dry biomass was determined and converted into Mg ha^{-1}. Input of C in each treatment was estimated by multiplying the biomass input with the C content in biomass, assumed to be 40% C in residues of all crops (Bolinder et al., 2007). The estimated amount of biomass and C applied under different treatments and from various sources is shown in Table 4.

2.5. Soil sampling and analysis

Soil samples were obtained from 0–10, 10–20 and 20–30 cm depths using a screw auger for analyzing the SOC content after the harvest of the rapeseed in 2014 and after the completion of four years of the experiment in 2016. Total C content was determined by the dry combustion method (Nelson and Sommers, 2005) using a TOC analyzer (ElementarVario Select, Germany). The SOC was assumed to be equal to the total C with negligible inorganic C concentrations as the soil pH was below 7 (Jagadamma and Lal, 2010). Soil bulk density (ρ_b) was determined by the core method (Blake and Hartge, 1986) at 0–10, 10–20 and 20–30 cm depths after oven dried at 105 ± 1 °C. The ρ_b and SOC were measured in 2014 before inclusion of the cowpea and in 2016 after completion of the experiment. The SOC pool (Mg ha^{-1}) at 0–10, 10–20, 20–30 and 0–30 cm depths were calculated using the equivalent soil mass method (Lee et al., 2009):

The soil mass was calculated by using following equation:

$$Ms = \rho b \times Df \times 10^4 \quad (1)$$

Where, M_s is the soil mass per unit area (Mg ha^{-1}), ρ_b is the soil bulk density (Mg m^{-3}), D_f is the depth of the fixed soil layer (m), and 10^4 is m^2 ha^{-1}.

The SOC pool of each layer was calculated using the following equation:

$$Mc = [Msi + (ESM - Msi)] \times Cci \times 10^{-3} \quad (2)$$

Where, M_C is the C mass per unit area (Mg C ha^{-1}), M_{si} is the soil mass of i_{th} layer (Mg ha^{-1}), the ESM is the equivalent soil mass (Mg ha^{-1}), C_{Ci} is the SOC (g kg^{-1}) the concentration of i_{th} layer and 10^{-3} is a product of the unit conversion factor (g Mg^{-1} and kg Mg^{-1}).

The C restoration with inclusion of cowpea was calculated by using the following equation:

$$\text{C restoration (\%)} = \frac{\text{Cc after cowpea} - \text{Cc before cowpea}}{\text{Cc before cowpea}} \times 100 \quad (3)$$

Where, Cc is the SOC concentration in the respective plots.

The SOC accumulation was computed as per Eq. (4):

$$\text{SOC accumulation (kg C ha}^{-1}) = \text{SOC final (kg C ha}^{-1}) - \text{SOC initial (kg C ha}^{-1}) \quad (4)$$

The sequestration of the SOC was computed as per Eq. (5):

$$\text{SOC sequestration (kg C ha}^{-1}\text{yr}^{-1}) = \frac{\text{SOC final(kg C ha}^{-1}) - \text{SOC initial (kg C ha}^{-1})}{\text{year of experimentation}} \quad (5)$$

The carbon retention efficiency (CRE) was calculated by using Eq. (6):

$$\text{CRE (\%)} = \frac{\text{SOC final (Mg C ha}^{-1}) - \text{SOC initial (Mg C ha}^{-1})}{\text{ECI}} \times 100 \quad (6)$$

The SOC final and the SOC initial represent SOC (Mg ha^{-1}) in the final and initial soil samples, respectively, and ECI is the estimated cumulative C input (Mg ha^{-1}) to soil between the initial and the final year of experimentation.

2.6. Statistical analysis

The statistical analysis of all data was performed using the GLM procedure of the SAS 9.4 (SAS Institute, 2003) to analyze the variance and to determine the statistical significance of the treatment effects. The least significant difference (LSD) at $p = 0.05$ was used to compare the treatment means. Since, cowpea as cover was included in 2014 before the sowing of rice in the system, the effect of cowpea biomass incorporation/retention was also analyzed. The effects observed in treatment as before and after cowpea were also analyzed by using the GLM procedure of SAS 9.4.

3. Results

3.1. Above ground biomass production

The above ground biomass production of rice and rapeseed didn't differ significantly ($p = 0.05$) among CT-RI and NT-RR (Table 3). However, the above ground cowpea biomass (sum of two years) was significantly affected by the tillage treatments (Table 3). Despite non-significant statistical differences, the above ground biomass production of rice was lower under the NT-RR (7.43 to 7.52 Mg ha^{-1}) system in the years 2012 and 2013 than those under CT-RI (7.77 to 7.82 Mg ha^{-1}). However, the NT-RR system produced more above ground biomass of

Table 3
Effect of tillage with residue management and mulches on above ground biomass production.

Treatment	Above ground biomass production (Mg ha^{-1})													
	2012-13			2013-14		2014-15			2015-16			Total		
	Rice	Rapeseed		Rice	Rapeseed	Rice	Rapeseed	Cowpea	Rice	Rapeseed	Cowpea	Rice	Rapeseed	Cowpea
Tillage														
CT-RI	7.77	4.19	7.82	4.31	8.15	4.42	4.67	8.20	4.49	5.12	31.93	17.40	9.79	
NT-RR	7.43	4.21	7.52	4.32	8.30	4.42	5.20	8.61	4.51	5.55	31.86	17.46	10.75	
SEm ±	0.11	0.07	0.09	0.05	0.10	0.03	0.05	0.09	0.07	0.05	0.20	0.22	0.11	
LSD ($p = 0.05$)	NS	NS	NS	NS	NS	NS	0.32	NS	NS	0.29	NS	NS	0.65	
Mulch														
SM	7.41	4.31	7.54	4.43	8.11	4.54	5.10	8.29	4.62	5.40	31.36	17.90	10.50	
GM	7.71	4.51	8.09	4.62	8.66	4.73	4.98	8.83	4.86	5.51	33.28	18.71	10.49	
BM	7.91	4.13	7.86	4.24	8.43	4.35	4.95	8.57	4.41	5.45	32.77	17.13	10.40	
NM	7.39	3.85	7.18	3.96	7.70	4.07	4.71	7.91	4.11	4.98	30.18	15.99	9.70	
SEm ±	0.17	0.16	0.17	0.14	0.17	0.14	0.15	0.17	0.15	0.11	0.59	0.58	0.34	
LSD ($p = 0.05$)	NS	0.48	0.52	0.44	0.51	0.44	NS	0.51	0.46	0.34	1.81	1.77	NS	

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

rice (8.30 to 8.61 Mg ha^{-1}) in 2014 and 2015 than those under the CT-RI (8.15 to 8.20 Mg ha^{-1}) (Table 3). Despite the lack of statistical differences, the total above ground biomass of rice (from sum of four years) was more under CT-RI (31.93 Mg ha^{-1}) than those under the NT-RR (31.86 Mg ha^{-1}). The above ground biomass of rapeseed was more under NT-RR (4.21 to 4.51 Mg ha^{-1}) system than those under the CT-RI (4.19 to 4.49 Mg ha^{-1}) across all the study years. The above ground biomass yield of cowpea was significantly higher under NT-RR (5.20 to 5.55 Mg ha^{-1}) than that under CT-RI (4.67 to 5.12 Mg ha^{-1}) during both years (2014 and 2015) (Table 3). The impact of mulches varied among crops in the system and over the years. The direct effect of mulch application was significant on the above ground biomass production of rice and its residual effect on above ground biomass of rapeseed (Table 3). However, the residual effect of mulching on the above ground biomass production of cowpea was non-significant in 2014 but significant in 2015. However, the total above ground biomass yield of cowpea was not significantly affected by the residual effect of mulching. The above ground biomass yield of rice was not influenced by diverse mulches during the first year of the experiment. However, from the year 2013 onwards, the above ground biomass yield of rice was more under mulched than that in the un-mulched plots (Table 3). Plots under GM produced (33.28 Mg ha^{-1}) significantly higher total above ground biomass of rice than those under SM (31.36 Mg ha^{-1}) and NM (30.18 Mg ha^{-1}) treatments (Table 3). However, there was no significant difference between the total above ground biomass yield of rice produced under GM (33.28 Mg ha^{-1}) and BM (32.77 Mg ha^{-1}) treated plots (Table 2). BM (cowpea) didn't affect the germination and plant stand of rice. The rapeseed grown with residual effects of GM produced (18.71 Mg ha^{-1}) significantly higher total above ground biomass than those under NM (15.99 Mg ha^{-1}).

3.2. Total biomass and carbon recycling

Total biomass and C added through the above and below ground biomass as well as with the mulch application, didn't differ significantly among tillage treatments. However, the biomass and C added was lower under NT-RR than that under CT-RI in 2013 and 2014. With the inclusion of cowpea in 2014, the amount of biomass and C recycled under NT-RR system increased which was more than that under CT-RI (Table 4). The overall total biomass and C added (for a sum of four years) were relatively higher under NT-RR than those under CT-RI system. Mulching had a significant effect on the amount of biomass and C recycled, resulting in significantly higher values under GM than those under NM. However, all mulch treatments were statistically at par with each other in respect to biomass production and C recycling (Table 4).

3.3. Soil bulk density and organic carbon content

Neither tillage nor mulch treatments significantly affected ρ_b at any soil depth (Suppl. Table 1). However, the soil ρ_b increased with increase in soil depth. The lowest ρ_b was observed at 0–10 cm and the highest at 20–30 cm depth. In general, ρ_b at 0–10, 10–20 and 20–30 cm soil layers

Table 4
Effect of tillage with residue management and mulches on biomass and carbon inputs.

Treatment	Biomass added through crop residue (Mg ha^{-1})					Total biomass added (Mg ha^{-1})					Carbon added (Mg ha^{-1})				
	2013	2014	2015	2016	Total	2013	2014	2015	2016	Total	2013	2014	2015	2016	Total
Tillage															
CT-RI	8.70	8.92	14.87	15.65	48.25	10.45	10.67	16.62	17.40	55.25	4.29	4.38	6.82	7.13	22.65
NT-RR	8.66	8.81	15.79	16.39	49.65	10.41	10.56	17.54	18.14	56.65	4.27	4.33	7.19	7.44	23.23
SEm ±	0.10	0.05	0.08	0.12	0.26	0.10	0.05	0.08	0.12	0.26	0.04	0.02	0.03	0.05	0.11
LSD ($p = 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Mulch															
SM	8.79	9.00	15.52	16.25	49.77	11.29	11.50	18.02	18.75	59.77	4.63	4.71	7.39	7.69	24.51
GM	8.63	9.33	15.91	16.71	50.58	11.13	11.83	18.41	19.21	60.58	4.56	4.85	7.55	7.88	24.84
BM	8.84	8.86	15.41	16.17	49.27	10.84	10.86	17.41	18.17	57.27	4.44	4.45	7.14	7.45	23.48
NM	8.46	8.28	14.49	14.95	46.18	8.46	8.28	14.49	14.95	46.18	3.47	3.39	5.94	6.13	18.93
SEm ±	0.22	0.14	0.23	0.26	0.75	0.22	0.14	0.23	0.26	0.75	0.09	0.06	0.10	0.11	0.31
LSD ($p = 0.05$)	0.68	0.43	0.72	0.79	2.30	0.68	0.43	0.72	0.79	2.30	0.28	0.18	0.29	0.33	0.94

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

Table 5
Effect of tillage with residue management and mulches on soil organic carbon.

Treatment	Soil organic carbon (g kg^{-1})					
	2014			2016		
	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm
Tillage						
CT-RI	6.4	6.3	6.0	6.6	6.5	6.1
NT-RR	6.8	6.2	5.9	7.4	6.3	6.0
SEm ±	0.1	0.1	0.1	0.1	0.1	0.1
LSD ($p = 0.05$)	NS	NS	NS	0.4	NS	NS
Mulch						
SM	6.7	6.2	6.0	7.1	6.4	6.1
GM	6.6	6.3	5.9	7.0	6.5	6.0
BM	6.7	6.3	5.9	7.0	6.5	6.1
NM	6.5	6.2	5.9	6.8	6.3	6.0
SEm ±	0.1	0.1	0.1	0.1	0.1	0.1
LSD ($p = 0.05$)	NS	NS	NS	0.2	NS	NS

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

Table 6
Effect of tillage with residue management and mulches on soil organic carbon pools.

Treatment	Soil organic carbon pools (Mg ha^{-1})					
	2014			2016		
	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm
Tillage						
CT-RI	9.80	9.50	9.09	10.06	9.87	9.26
NT-RR	10.34	9.49	8.97	11.21	9.65	9.06
SEm ±	0.07	0.04	0.10	0.09	0.10	0.09
LSD ($p = 0.05$)	0.41	NS	NS	0.54	NS	NS
Mulch						
SM	10.16	9.48	9.14	10.85	9.78	9.21
GM	10.10	9.56	9.02	10.67	9.86	9.16
BM	10.12	9.52	8.98	10.66	9.82	9.20
NM	9.89	9.43	8.98	10.36	9.57	9.07
SEm ±	0.11	0.14	0.10	0.10	0.17	0.11
LSD ($p = 0.05$)	NS	NS	NS	0.29	NS	NS

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

ranged from 1.40 to 1.42, 1.44–1.46 and 1.47-1.48 Mg m^{-3}, respectively. Incorporation of cowpeas in the rotation didn't affect ρ_b in soil under the rice-rapeseed cropping system at any depth.

The SOC content was higher in 0–10 cm as compared to that in10–20 cm and 20–30 cm layers. Tillage and mulching didn't affect the SOC content in all soil depths in 2014. In 2016, however, the SOC content in 0–10 cm depth was significantly higher in soil under NT-RR than that under CT-RI (Table 5). The SOC content didn't change significantly among tillage treatments between 10 and 30 cm depths. The SOC content ranged between 6.4 to 6.8, 6.2 to 6.3 and 5.9 to 6.0 g kg^{-1} in 0–10 cm, 10–20 cm and 20–30 cm soil depths, respectively, irrespective of the tillage and mulch application in 2014. However, in 2016, the SOC content was more in all soil layers than those recorded in 2014. It ranged from 6.6 to 7.4, 6.3 to 6.5 and 6.0 to 6.1 g kg^{-1} in 0–10 cm, 10–20 cm and 20–30 cm soil depths, respectively, across the tillage and mulch treatments (Table 5). While the effects of tillage was not significant in 2014, both CT-RI and NT-RR increased the SOC content over the antecedent values by 1.59 to 7.94%, 1.64 to 3.28% and 0 to 1.69% in 0–10 cm, 10–20 cm and 20–30 cm soil depths, respectively. The magnitude of increase in SOC content under the NT-RR was more in the surface (0–10 cm) than those in sub-soil layers (10–20 and 20–30 cm). In contrast, SOC in CT-RI was higher in sub-soil layers (10–20 and 20–30 cm depth) than that in 0–10 cm layer. The NT-RR system increased the SOC content in 0–10 cm depth by 7.9 and 6.3% over the initial value and those under CT-RI, respectively in 2014 (Table 5). These values were 17.5 and 12.1% higher over the SOC of the initial soil samples and that in soil under the CT-RI, respectively in 2016 (Table 5). Mulching didn't have a significant effect on the SOC content, except in 0–10 cm soil depth in 2016. The SM treated plots had higher SOC content over those under NM plots in 0–10 cm depth. The trend of the SOC content changed with the inclusion of the pre-monsoon cowpea cover crop in 3rd cropping cycle, resulting in a significant change of the SOC content to 20 cm depth. In comparison, the effect of tillage and mulch on SOC content was limited to 10 cm depth. However, the SOC content didn't change significantly in 20–30 cm depth even after the inclusion of cowpea as cover crop in the system. Retention of cowpea cover crop biomass increased the SOC content by 5.4, 2.5 and 1.3% in 0–10, 10–20 and 20–30 cm soil depths, respectively over SOC concentrations before the inclusion of cowpea (6.6, 6.3 and 5.9 g kg^{-1} of 0–10 cm, 10–20 cm and 20–30 cm soil depths, respectively) in the system. The C restoration was also higher after the inclusion of cowpea cover crop (3.33%) as compared to those prior to introduction of cowpea (0.99%) (Fig. 3a).

3.4. Soil organic carbon pool

The SOC pool in different layers (0–10 cm, 10–20 cm and 20–30 cm) differed among tillage and mulch treatments (Table 6). The SOC pool

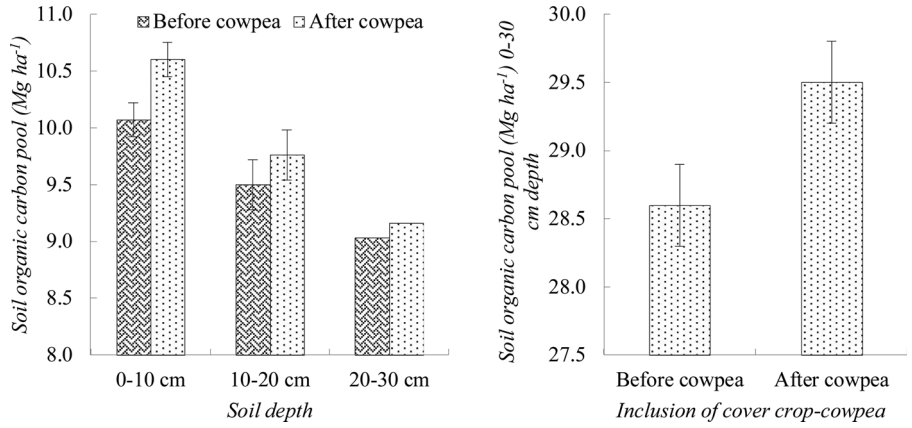

Fig. 2. Effect of cowpea cover crop inclusion in rice-rapeseed cropping system on soil organic carbon pool.
The vertical error bars indicate LSD at $p = 0.05$

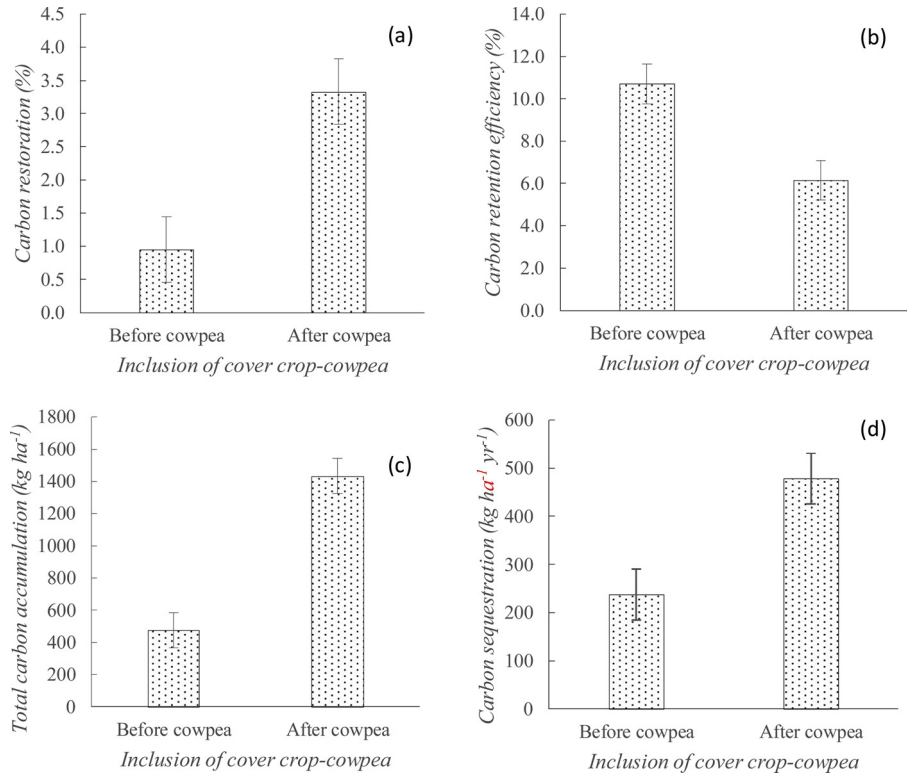

Fig. 3. Effect of cowpea cover crop inclusion in rice-rapeseed cropping system on carbon restoration (a), carbon retention efficiency (b), total carbon accumulation (c) and carbon sequestration rate (d).
The vertical error bars indicate LSD at $p = 0.05$

was higher in 0–10 cm than those under 10–20 and 20–30 cm layers during 2014 and 2016. The NT-RR system recorded significantly higher SOC pool of 10.3 and 11.2 Mg ha^{-1} in 0–10 cm depth than those under CT-RI (9.8 and 10.1 Mg ha^{-1}), respectively in 2014 and 2016 (Table 6). However, the SOC pool didn't vary significantly between the NT-RR and CT-RL in 10–20 cm and 20–30 cm depths during both the years. The soils under SM treated plots had the highest SOC pool in 0–10 cm depth (10.8 Mg ha^{-1}) than that under other mulch treatments in 2016. The inclusion of cowpea cover crop and incorporation/retention of its biomass had similar effects on SOC pool as it had on the SOC content (Fig. 2). The SOC pools were increased by 5.0, 2.7 and 1.4% in 0–10, 10–20 and 20–30 cm depth, respectively over SOC pool over prior to inclusion of the cowpea cover crop. The total SOC pool in 0–30 cm depth ranged from 28.3 to 28.8 Mg ha^{-1} and 29.0 to 29.9 Mg ha^{-1} during 2014 and 2016, respectively (Table 7). However, neither tillage nor mulching affected the SOC pool in 0–30 cm depth in 2014. In 2016, however, the SOC pool changed significantly under different tillage and mulch treatments. The SOC pool in 0–30 cm depth for the NT-RR system was increased by 6.4% and 2.5% over that of the initial value and that under CT-RI, respectively in 2016. The application of mulch increased the SOC pool by 5.5 to 6.1% and 2.3 to 2.8% over the initial SOC pool and that under NM, respectively. The SM treated plots had the highest SOC pool among diverse mulch treated plots. However, the SOC pool under SM treated plots was not significantly different from those under the GM and BM treated plots. The SOC pool in 0–30 cm depth also substantially increased (0.9 Mg ha^{-1}) due to the inclusion of cowpea cover crop in the rice-rapeseed system (Fig. 2).

Table 7
Effect of tillage with residue management and mulches on soil organic carbon pool, accumulation, sequestration and retention efficiency at 0–30 cm soil depth.

Treatment	Total carbon pools (Mg ha^{-1})		Carbon accumulations (kg ha^{-1})		Carbon sequestration (kg ha^{-1}yr^{-1})		Carbon retention efficiency (%)	
	2014	2016	2014	2016	2014	2016	2014	2016
Initial carbon pool in 2012	28.12							
Tillage								
CT-RI	28.39	29.18	268.6	1062.9	134.3	265.7	2.68	4.59
NT-RR	28.80	29.92	681.8	1800.9	340.9	450.2	8.04	7.70
SEm ±	0.15	0.08	17.6	10.7	8.8	2.7	0.20	0.05
LSD ($p = 0.05$)	NS	0.49	107.0	65.1	53.5	16.3	1.23	0.28
Mulch								
SM	28.78	29.83	678.7	1712.0	339.4	428.0	7.26	6.94
GM	28.68	29.69	555.8	1566.6	277.9	391.6	6.09	6.35
BM	28.62	29.68	501.1	1563.6	250.6	390.9	5.68	6.64
NM	28.30	29.01	165.2	885.5	82.6	221.4	2.41	4.66
SEm ±	0.24	0.19	32.7	100.8	16.4	25.2	0.41	0.43
LSD ($p = 0.05$)	NS	0.59	100.7	310.5	50.4	77.6	1.26	1.33

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

3.5. Carbon sequestration and retention efficiency

Tillage (NT-RR and CT-RI) and mulch treatments significantly affected the total C accumulation, sequestration rates and the CRE (Table 7). The NT-RR system accumulated more SOC in both 2014 and 2016 (682 and 1801 kg ha^{-1}, respectively) than those under the CT-RI (268.6 and 1062.9 kg ha^{-1}, respectively) (Table 7). The rate of C sequestration was low during the first two years as compared those estimated at the completion of the experiment in 2016. The C sequestration rate varied among tillage treatments from 134 to 341 kg ha^{-1} yr^{-1} and 266 to 450 kg ha^{-1} yr^{-1} in 2014 and 2016, respectively. The NT-RR systems sequestrated more C than those under the CT-RI. The NT-RR system had higher CRE (8.04 and 7.70% in 2014 and 2016, respectively) than that under CT-RI (Table 8). Further, CRE was relatively more in 2014 than that in 2016 (Table 7). The SM treated plots accumulated more C than those under other mulch and NM treatments. Similar trends were observed in C sequestration and the CRE as that by C accumulation with the application of mulch. The amount of total SOC accumulated (1432 C kg ha^{-1}) after inclusion of cowpea before rice was three times higher than the antecedent rate (Fig. 3 c). The rate of C sequestration (478 kg C ha^{-1} yr^{-1}) was doubled with inclusion of cowpea as cover crop and incorporation/retention of its biomass than prior to addition of cowpea (Fig. 3d). However, CRE decreased from 10.7 to 6.1% with the inclusion of the cowpea during the pre-rainy season in rice-rapeseed system (Fig. 3b).

4. Discussion

4.1. Production of above ground biomass and recycling of carbon

The production of plant biomass is directly related to soil health and the micro environment. Tillage and mulch play a vital role in the management and regulation of soil health and environment (Lal, 2016). In the present study, the biomass yield of rice and rapeseed obtained under the NT-RR didn't differ statistically from those under CT-RI, however, cowpea biomass yield was significantly higher under NT-RR than that under the CT-RI. These trends may be attributed to improved plant growth under NT-RR due to favorable soil properties including better soil structure and aggregation, increased soil moisture, reduced risks of soil erosion, increased SOM, and high macro and micro biodiversity (Huang et al., 2008; Lal, 2016). Several researchers have also reported the yield benefits of a range of crops under the NT-RR system (Jalota et al., 2008; Singh et al., 2016; Das et al., 2017). However, the effects of NT-RR systems on crops may vary among soils and climates. The higher biomass yield of cowpea under the NT-RR system may be ascribed to better response of legumes than non-legume crops to NT-RR. The minimal soil disturbance and soil cover protect the biological components of soil and enhance nutrient availability for microbial growth, which might have attributed to a higher biomass yield under NT-RR systems. Higher the biomass yield of all crops under mulched than unmulched treatments might be attributed to increased SOM, improved soil aggregation, moisture conservation, porosity and pore size distribution, infiltration and decrease in ρ_b (Jalota et al., 2008; Singh et al., 2016; Das et al., 2017). The highest biomass yield of all the crops under GM might be due to more availability of N since *Gliricidia* leaves contain high N (2.5%), which may stimulate growth by supplementing the N nutrition in plants (Huang et al., 2012). The production of high above- and below-ground biomass and its retention are essential pre-requisites to SOC restoration (Deng et al., 2017) and improvement of the soil health. The data presented in Table 3 indicated that the adoption of NT-RR and mulch systems increased the above ground biomass production. Therefore, production and retention of additional biomass is an important strategy for sequestrating atmospheric CO_2 in the biosphere (Deng et al., 2017) for mitigation of climate change.

Recycling of biomass into the soil is indispensable for restoring SOC pool and maintaining the equilibrium in soil-plant-atmosphere continuum (Schulze, 2006). The variation in the amount of biomass and added C in the present study were mainly due to the variation in production of the above and below ground biomass of the same under different tillage and mulch treatments. The amount of biomass added through crop residues along with mulch (total biomass) and the C added was the highest under the NT-RR and GM systems than those under CT-RI and other mulched plots. The production of more crop biomass under NT-RR and GM were responsible for addition of higher biomass and C under the respective treatments.

4.2. Soil bulk density, soil organic carbon and pool

Reported impacts of tillage systems on soil ρ_b are not always consistent mainly due to variations in pedo-climatic conditions, farming practices and large spatial variability. Several studies have reported a higher ρ_b in surface layer under NT while compared to that under CT in different cropping systems (Gathala et al., 2011; Jat et al., 2013). The positive effects of the retention of crop residues on soil ρ_b in surface layer are reported widely (Govaerts et al., 2009; Mi et al., 2016; Nawaz et al., 2017). In the present study, the soil ρ_b was not significantly affected by tillage systems, probably because of the short duration of the study. Further, the NT-RR system had highest SOC content and pool (0–10 cm depth) which was attributed to addition of more biomass and C under NT-RR than those under the CT-RI. The production and

retention of biomass under NT have been reported to increase the SOC content and pool, even on a short-term basis (Mulvaney et al., 2017). The production of higher above- and below- ground biomass and its subsequent recycling might have been responsible for higher SOC concentrations, pool, accumulation and sequestration rate under the NT-RR and mulch systems than those under CT-RI and no mulch systems (Deng et al., 2017). The data presented herein indicate that the rate of SOC sequestration, SOC content, pool and accumulation were enhanced with the inclusion of the cowpea in the cropping system during the last two years of study. The increase in the number of crops grown in sequence in the system generated more biomass for C recycling (Novelli et al., 2017), thereby increasing the SOC content and pool compared to that of the soil under mono-cropping of rice. Further, the biomass (from residues, mulch and cover crops) is the food and energy source for soil microbes and facilitates soil aggregation when retained/incorporated into the soils (Six et al., 2002). The increased activity of microbes encourages the binding of organic matter and particles of soil into macro and micro aggregates (Six et al., 2002), leading to an enhancement in the aggregate stability, restoration of unstable C and finally improvement in the SOC content (Razafimbelo et al., 2008) and soil C sequestration (Koga and Tsuji, 2009). Furthermore, the SOC dynamics depends on the tillage intensity and amount of residue retained on the surface (Srinivasan et al., 2012). Lower SOC pool under CT-RI than those under NT-RR can be attributed to intensive tillage practices that favor organic matter mineralization through higher temperatures and the lower physical protection causing release and depletion of nutrients (Hassan et al., 2016) and loss of C as CO_2 due to oxidation (Alvarez et al., 2014). Further, repeated tillage under CT breaks down C-rich macro aggregates into micro aggregates which have free organic matter particles and relatively lower C retention capacity (Srinivasan et al., 2012; Sheehy et al., 2015). The high SOC content and pool in sub-soil (10–20 and 20–30 cm) layers under CT-RI as compared to that under NT-RR might be due to the incorporation of C rich crop residues under the CT-RI systems (Hassan et al., 2016) and its almost of even distribution in different soil layers. The higher SOC content under CT in sub- soil layer than that in soil under the NT system have also been previously reported (Blanco-Canqui et al., 2011; Muñoz-Romero et al., 2017). Positive impacts of mulching on SOC concentration and the pool only up to 10 cm depth may be attributed to the fact that the amount of C released through decomposition and mineralization may be limited mostly to the surface layer (Fontaine et al., 2007). Consequently, mulches applied on the surface had less influence on soil properties in sub-soil layer (below 10 cm depth). The data presented herein also indicated that the SOC content, pool, and sequestration differed among the mulch types. The highest SOC content and pool in 0–10 cm soil layer in soil under SM might be due to slow decomposition of rice straw due to its higher C: N ratio as compared to other mulches (Chen et al., 2017). The SOC content and pool may also be affected by the quantity, type and methods of mulch application (Mulvaney et al., 2017). The lack of statistical differences in the SOC content and pool among BM, SM and GM were mainly attributed to the variation in C: N ratios of biomass applied through various mulch treatments (Liang et al., 2018). Thus, the low application rate of biomass (associated with its *in-situ* production potential at 40 days of crop duration) under BM sequestered SOC at almost equal amounts while compared to that under SM and GM. It is widely recognized that, the best strategy of SOC sequestration is the *in-situ* biomass production and retention/incorporation in the soil (Lal, 2016). Therefore, the BM is a feasible option for sequestration of atmospheric CO_2 and restoration of SOC pool to the antecedent level. This is especially important considering the fact that paddy straw has competing and alternate uses as cattle feed in some regions and farmers' may not leave a significant quantity of it as mulch. Hence, as trade-off between mulching and soil fertility build up, BM instead of SM seems to be an acceptable approach.

The data presented herein also indicate that, the inclusion of the cowpea cover crop in rice-rapeseed cropping system increased the SOC content and pool compared with those prior to the inclusion of cowpea in the rotation cycle. This trend may be attributed to the production of additional biomass by cowpea. Despite the fact that tillage and mulches had a significant effect on SOC content at 0–10 cm depth, the inclusion of cowpea thus increased the SOC content for upto 20 cm soil depth due to its deep root system, which sequestrated SOC in sub-soil layers than that by the surface retention of mulches (Stagnari et al., 2017). The rate of SOC restoration under tillage and mulches didn't change significantly, however, the C restoration significantly increased when cowpea was included as cover crop in the rice-rapeseed cropping system. The increase in C-restoration, from 0.95% to 3.33%, is mainly attributed to the addition of C through cowpea (Stagnari et al., 2017). In addition to C restoration, the total C accumulation and rate of C sequestration were also doubled with the addition of cowpea cover crop in the system which attributed to contribution of legume to C stabilization because of low C: N ratio (Lal, 2016). The SOC retention rates of 2.41 to 8.04% in 2014 and 4.59 to 7.70% in 2016 in the present study are lower than those reported by other experiments conducted in the sub temperate Himalayan region (Kundu et al., 2007; Bhattacharyya et al., 2009) and in the humid Indo-Gangetic plains of India (Majumder et al., 2008). This trend might be due to prevailing high temperatures in the study site that favored the faster decomposition of the SOM. Thus, there is a higher requirement of high amount of plant biomass C in this region to maintain an antecedent level of C and to increase the rate of SOC sequestration.

4.3. Environmental implications of soil carbon sequestration in the region

Global rates of SOC sequestration are reported to range from 110 to 3004 kg C ha^{-1} yr^{-1} under different management practices with a mean sequestration rate of ~540 kg C ha^{-1} yr^{-1} (Lal et al., 2003; Conant et al., 2001). The SOC sequestration rates of 170 to 550 kg ha^{-1} yr^{-1} have been reported for the Indo-Gangetic plains of India (Das et al., 2013). Further, SOC-sequestration potential is strongly affected by the soil type, clay content and mineralogy, cropping systems, crop species, tillage, climate and other management practices (Conant et al., 2001). The data presented herein indicate that the total SOC retention rates under the tillage treatments ranged from 266 to 450 kg C ha^{-1} yr^{-1} with the highest rate being achieved under the NT-RR. Therefore, NT with residue retention has a large potential of increasing the SOC content in agro-ecosystem of the study region. The application of mulches also significantly influenced C retention, and the rate of C sequestration ranged from 221 to 428 kg C ha^{-1} yr^{-1} with the highest sequestration rate under SM. The shifting cultivation, deforestation and residue/biomass burning are the common practices in the hilly areas of the EHR of India. The transformation of forest land (both primary and secondary forests) to agriculture lands (crop lands, plantation crop land, etc.) have been reported to reduce SOC pool by 25 to 30% in the tropics (Don et al., 2011). Furthermore, burning of plant biomass/vegetation can reduce the surface SOC pool by 41% in hilly areas of other regions similar to the EHR of India (Novara et al., 2011). In the present study on 4-year impact of continuous NT-RR system, the SOC pool increased to 29.9 Mg ha^{-1} compared to the initial SOC pool of 28.1 Mg ha^{-1}. Thus, about 1800 kg of C was accumulated in the soils of NT-RR at the rate of 450 kg C ha^{-1} yr^{-1} up to 30 cm depth. Choudhury et al. (2016) reported that the average SOC pool across the land use systems in the EHR of India varied significantly ($p < 0.05$) from 27.4 to 42.1 Mg ha^{-1} with the highest pool observed under grass land (42.1 Mg ha^{-1}) followed by that under the mixed dense forest (35.2 Mg ha^{-1}) to a 40 cm depth. Therefore, to move towards the antecedent level of SOC pool as those under grass land or forest land, adoption of NT with residue retention and mulching must be continuously practiced for 15 to 30 years in sloping uplands of the EHR, India. The data presented herein show that the adoption of the NT-RR increased SOC pool by 6.8 to 13.7 Mg C ha^{-1} in 0–30 cm depth during a period of 15–30 years. These values are equivalent to sequestration of 25 to 50 Mg CO_2 ha^{-1} (Das et al., 2013).

Furthermore, the higher SOC sequestration rate, of ~1.4 Mg CO_2 ha^{-1} yr^{-1} under NT-RR compared with that of 0.9 Mg CO_2 ha^{-1} yr^{-1} under the CT-RI can mitigate climate change by off-setting anthropogenic emissions. Additionally, mulch application sequestered much higher CO_2 (1.2 to 1.4 Mg ha^{-1} yr^{-1}) relative to those under the NM (0.6 Mg CO_2 kg ha^{-1} yr^{-1}) treatment. Thus, the adoption of CA in the fragile ecosystems of the study region may prove to be a boon for mitigating climate change by restoring the SOC pool while also restoring soil health and the agronomic productivity through efficient utilization of available crops, weed and other biomass in the region.

5. Conclusion

The data presented in the study proved the hypothesis that NT-RR with mulch, increased biomass production and retained more C than that with CT-RI. The NT-RR enhanced SOC content, pool, sequestration rate (450.2 kg ha^{-1} yr^{-1}) and CRE (7.7%) in soils compared with those for the CT-RI treatment. Further, the SM produced more biomass, and also recycled more C leading to higher SOC content and pool than those under NM. However, BM was equally effective in the enhancing of the SOC concentration, pool, sequestration rate and CRE, and these parameters were at par with those under SM and GM. The addition of cowpea as cover crop increased the total C accumulation by three times and C sequestration by two times relative to those prior to the inclusion of the cowpea. Therefore, the present study provided information to the stakeholders and policy-makers to develop a sustainable crop production technology with the inclusion of NT and residue retention along with legume co-culture (BM of cowpea) during rice and the inclusion of cowpea as a cover crop during pre-monsoon season prior to rice to improve SOC sequestration and soil health. These improved systems would minimize risks of soil degradation and decline of SOC pool under rice monoculture in upland agro-ecosystems of the EHR. In addition, the study also identified sustainable options for restoring/preserving the precious SOC resource for mitigating the anthropogenic climate change.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2019.02.001.

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